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Asteroseismic determination of the physical characteristics of the planetary system host HR 8799 (λ Bootis nature and age)

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HR 8799 is a λ Bootis, γ Doradus star hosting a planetary system and a debris disk with two rings. This makes this system a very interesting target for asteroseismic studies. In particular, this work is devoted to the determination of the internal metallicity of this star, linked with its λ Bootis nature, and its age, taking the advantage of its γ Doradus-type pulsations. To do so we have used the equilibrium code CESAM and the non-adiabatic pulsational code GraCo. We have applied the Frequency Ratio Method and the Time Dependent Convection theory to estimate the mode identification, the Brunt-Vaïsälä frequency integral and the mode instability, making a selection of the possible models fulfilling all observational constraints. Using the position of the star in the HR diagram, the solar metallicity models is discarded. This result contradicts one of the main assumptions of the most accepted hypothesis explaining the λ Bootis nature, the accretion/diffusion of gas from a star with solar metallicity. Therefore, in sight of these new results, a revision of this hypothesis is needed. The inclusion of accurate internal chemical mixing is necessary. The use of the asteroseismological constraints provides a very accurate determination of the physical characteristics of HR 8799: an age in the ranges [1123, 1625] and [26, 430] Myr, and a mass in the ranges [1.32, 1.33] and [1.44, 1.45] $M_\odot$, respectively, depending on the visual angle i. The determination of this angle and more accurate multicolor photometric observations can definitively fix the mass, metallicity and age of this star. In particular, an accurate age estimation is needed for a correct understanding of the planetary system. In our study we have found that the age widely used for modelling the system is unlike.

1 Introduction

Accurate ages stars hosting extrasolar planets are useful for, e.g., obtaining theoretical constraints on tidal interactions between Hot Jupiters and their hosts, dynamical modelling of exoplanetary systems, predicting exoplanetary luminosities, etc, since they constrain the age of the planets. The eventual aim of refining the age determination of the stars is to obtain more information on planetary system formation to discern between the different scenarios. Several methods can be applied to determine ages of stars, like the use of chromospheric activity proxies, lithium depletion, evolutionary track fitting, etc (Barrado y Navascués 1998; Barrado y Navascués et al. 1999). Nonetheless, for pulsating stars, asteroseismology is the best and most accurate method we know that provides mass, radii and ages with an accuracy order of magnitudes larger than obtained with other methods in the literature (Stello et al. 2009).

The discovery by Marois et al. (2008), of the first planetary system by direct imaging around HR 8799 has made the age, mass and metallicity determination of this star a very important task. That was the starting point of a set of approximately ten studies about this system during 2009, none of them from an asteroseismic point of view, even considering that there are three detected pulsational frequencies (Zerbi et al. 1999) that can be used to better understand the host star.

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The main characteristics of this system are:

- The host star is a A5 Main Sequence star (Gray & Kaye 1999), γ Doradus pulsator (Zerbi et al. 1999), and it has λ Bootis-type surface chemical peculiarities (Sadakane 2006).
- There are three sub-stellar objects orbiting the host star. They have been observed using direct imaging (Marois et al. 2008).
- The system has a debris disk with two rings, one inner and another further out the three orbiting objects (Chen et al. 2009).
- From a dynamical point of view, the stability of the system is a challenge, regarding the mass given for the objects and star, and the age assumed for the system (Reidemeister et al. 2009).

These four characteristics make the planetary system HR 8799 a very interesting one, with many challenges to understand its structure, formation and evolution. In particular, the age of the star (and consequently of the system)

is one of the key quantities for all the studies done around HR 8799, since it is directly related with the mass of the orbiting objects, and it imposes a goal for the dynamical stability of the system.

In two recent works (Moya et al., 2010a, b), a comprehensive modelling of HR8799 using asteroseismology has been done. The main conclusions are the following:

- The use of asteroseismological observational data imposes large constraints to the acceptable models of stellar internal structure.
- The actual uncertainty in the knowledge of the age of HR 8799 is larger than shown in the literature. Only less than 20% of the accepted model using all the observational constraints have an age in the range estimated by other works.
- The internal subsolar metallicity obtained for the star provides some keys to understand the λ Bootis nature.

These works have shown the enormous potential of the use of asteroseismology to understand this system and others. Nevertheless, these studies cannot be conclusive due to the poor asteroseismic observational available data. There is not very accurate multicolour photometric observations. Therefore, additional observations are imperative to provide better asteroseismological constraints.

2 Observational data

The A5 V star HR 8799 has been extensively studied in the last years. The first studies of this star were done in the context of asteroseismology. Schuster & Nissen (1986) firstly reported HR 8799 as a possible SX Phoenicis type. Zerbi et al. (1999) observed this star in a multisite multicolour photometric campaign, with Strömgren filters, and found three independent pulsational frequencies ($f_1 = 1.9791\ \mathrm{c\,d^{-1}}$, $f_2 = 1.7268\ \mathrm{c\,d^{-1}}$, and $f_3 = 1.6498\ \mathrm{c\,d^{-1}}$, units are cycles per day), making it one of the 12 first γ Doradus pulsators known (Kaye et al 1999). This pulsating stellar group is composed of Main Sequence (MS) stars in the lower part of the classical instability strip. Their pulsation modes have periods in the range [0.5,3] days, that is, they are asymptotic g-mode pulsators. Gray & Kaye (1999) obtained an optical spectrum of HR 8799, and assigned an spectral type of kA5 hF0 mA5 V λ Bootis, reporting an atmospheric metallicity of [M/H]=-0.47 and accurate values of the stellar luminosity, $T_{\rm eff}$, and $\log g$ (see Table 1) . They also noted that HR 8799 may be also a Vega-type star, characterized by a far IR excess due to a debris disk. Sadakane (2006) developed a deep study of the metal abundances of this star, confirming its λ Bootis nature (with surface chemical peculiarities, Paunzen 2003). HR 8799 is one of the three λ Bootis stars with γ Doradus pulsations (Rodríguez et al. 2006a, b)

The use of different bolometric corrections changes significantly the value of the luminosity of the star. Using the Virtual observatory tool VOSA (Bayo et al. 2008), models with realistic metallicities best fitting the observations provide a luminosity only 0.1 $L/L_\odot$ larger than that given in Table 1 and, therefore, within the errors. On the other hand, the use of different parallaxes in the literature changes the value of the absolute magnitude of this star by less than 0.1 $L/L_\odot$ (see Moya et al. 2010a for details).

Table 1 Physical characteristics of HR 8799

$T_{\rm eff}$ (K)	7430±75	
$\log g$ ($\mathrm{cm\,s^{-2}}$)	4.35±0.05	Gray & Kaye 1999
L($\mathrm{L_\odot}$)	4.92±0.41	
v sin i ($\mathrm{km\,s^{-1}}$)	37.5±2	Kaye & Strassmeier 1998
π (mas)	25.38±0.85	van Leeuwen 2007

3 Modelling of the observational data

We have developed a grid of equilibrium models obtained with the CESAM code (Morel & Lebreton 2008). We vary the mass (in the range [1.25, 2.10] $M_\odot$ with steps of 0.01 $M_\odot$), the metallicity (with values [M/H]=0.08, -0.12, -0.32, and -0.52), the Mixing-Length parameter MLT (values 0.5, 1, and 1.5), and the overshooting (values 0.1, 0.2, and 0.3). The internal metallicity has been regarded as a free parameter due to the λ Bootis nature of the star, which hides its internal abundances. The mass, estimated to be 1.47 ± 0.3 $M_\odot$ by Gray & Kaye 1999, has been also regarded as a free parameter since it has not been directly determined.

The pulsational analysis has been developed using the non-adiabatic pulsational code GraCo (Moya et al. 2004; Moya & Garrido 2008). Both codes have been tested in the work of the ESTA activity (Evolution and Asteroseismic Tools Activities, Lebreton et al. 2008; Moya et al. 2008). Using these tools, we performed a theoretical study of HR 8799 in an attempt at constraining physical and theoretical parameters. In this work we will follow the same scheme used for the study of the δ Scuti pulsators RV Arietis, 29 Cygnis and 9 Aurigae (Casas et al. 2006; Casas et al. 2009; Moya et al. 2006). Taking advantage of the γ Doradus pulsations, we have used the Frequency Ratio Method (Moya et al. 2005) to estimate the possible mode identification of the observed modes, and the Time Dependent Convection (Gricahcéne et al. 2005) for the analysis of the mode instability and the possible spherical order comparing with observed multicolour photometry. All these techniques provide additional constraints to the position of the star in the HR diagram, reducing the possible physical characteristics of the models fulfilling all the observations.

4 On the λ Bootis nature of HR 8799

The first selection of models was done imposing only the spectroscopic constraints displayed in Table 1. This selection shows that there are no models with solar metallicity fulfilling observations, since the stellar luminosity derived is smaller than any of the possible luminosities of models

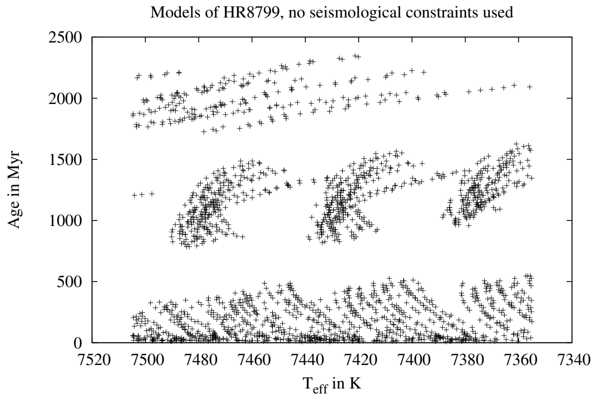

Fig. 1 $T_{\rm eff}$ - Age diagram for the models of our grid fulfilling the spectroscopic observations, i.e., T_{eff}, $\log g$ and luminosity displayed in Table 2. The age range obtained is [10, 2337] Myr.

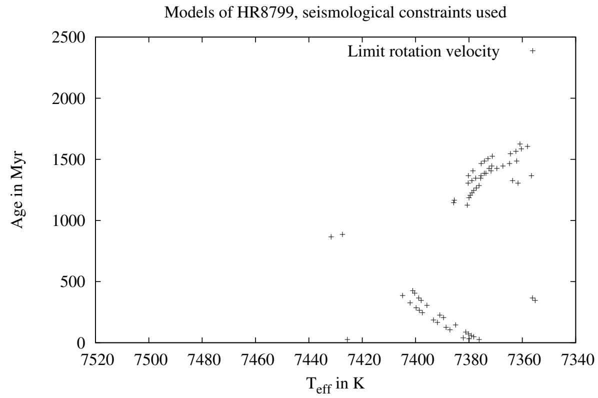

Fig. 2 $T_{\rm eff}$ - Age diagram for the models of our grid fulfilling the spectroscopic observations plus all the asteroseismological constraints (FRM + multicolour photometry + instability analysis, see Moya et al. 2010a, b) for a rotation velocity $V_{\rm rot} \approx 60 {\rm km\,s^{-1}}$. The age ranges obtained are $[1123, 1625]$, $[26, 430]$ Myr

with solar metallicity. This contradicts the main assumption of the theories explaining the λ Bootis nature, i.e. the accretion/diffusion scenario where these stars have solar metallicity, whereas the observed abundances are due to surface phenomena (Turcotte & Charbonneau 1993).

The result of our work, discarding solar metallicity as the internal metallicity of the star, together with the fact that some λ Bootis stars have debris disks not connected with the star (Chen et al. 2009), makes this accretion/diffusion scenario unlikely, but not negligible (Su et al. 2009). Therefore, the study of internal chemical mixing processes seems to be the key to explain the λ Bootis nature, at least for HR 8799, as the solar abundances for C, N, O and S observed on its surface have still to be explained.

5 On the mass and age of HR 8799

There are several age determinations of the age of HR 8799 in the literature (see Moya et al. 2010b for a complete review), most of them estimating its age in a range around [30,160] Myr. The most robust determination found is the kinematic age determination (UVW). But the authors warned that this method is not always reliable.

The main complementary argument to that statistical determination is the position of the star in the HR diagram. In Moya et al. 2010b we have demostrated that this procedure does not provide accurate age estimations due to the λ Bootis nature of HR 8799 (Fig. 1). This result was previusly pointed out by Song et al. (2001), how stimated the age of HR 8799 in the range [50,1128] Myr. In Section 4 we saw that this nature hides the real internal metallicity of the star. The main consequence of this result is that the models fulfilling observations are in a range of ages [10,2337] Myr, a much broader range that one estimated by other authors of [30,160] Myr (Marois et al. 2008). Only a small amount (18.1%) of models in our representative grid have ages in the range mainly claimed in the literature.

Therefore we need aditional constraints for an accurate estimation of the age and mass of this star. We have explained in Section 3 that one of the techniques used for this study is the Frequency Ratio Method. This method has a range of applicability deppending on the stellar rotation velocity (Suárez et al. 2005; Moya et al. 2010a). For inclination angles around $i = 36°$ (corresponding to a stellar rotation velocity of $V_{\rm rot} \approx 60 {\rm km\,s^{-1}}$ (Kaye & Strassmeier 1998), the limit for the FRM to be accurately applied), the models fulfilling all the observational constraints have masses in two separate ranges of M=[1.32, 1.33], [1.44, 1.45] $M_\odot$. The age of the system is constrained in two separate ranges: [1123, 1625] Myr and [26, 430] Myr respectively (Fig. 2). A percentage of 16.7% of the models are in the range given in the literature. A consequence of this result is that, in the case of the youngest age range, the predicted masses of the observed planets are [5,14] $M_{\rm Jup}$ for the most luminous planets, and [3,13] $M_{\rm Jup}$ for the less luminous one. The oldest age range, the most probable from the point of view of the present study, predicts masses for the three objects in the brown dwarfs domain (see Fig. 4 of Marois et al. 2008).

The lack of an accurate determination of the inclination angle is the main source of uncertainty of the present study. This angle has not been unambiguously obtained up to now, and its value would say whether the results of this study are actually applicable, and then, it can provide a very accurate determination of the age and mass of the star.

6 Conclusions

The accurate determination of the mass, age and internal metallicity of a star hosting a planet or a planetary system is a necessary step to understand the formation and evolution of that planetary system. If the hosting star pulsates, the use

Table 2 Acceptable models depending on the physical constraints. In the complete procedure case, the first (second) mass range is linked with the first (second) age range shown.

Constraint	Mass in $M_\odot$	Age in Myr	% of models with $[30, 160]$ in Myr
HR position	[1.25,1.27],[1.32,1.35],[1.40,1.48]	[10, 2337]	18.1
Complete procedure	[1.32, 1.33], [1.44, 1.45]	$[1123, 1625]$, $[26, 430]$	16.7

of asteroseismology can provide these physical quantities with an accuracy hardly obtained with other techniques.

The case of HR 8799 is a excellent example of this benefit provided by asteroseismology. In two recent works (Moya et al. 2010a, b), the first comprehensive asteroseismologic study of the planetary system host HR 8799, a λ Bootis star presenting γ Doradus pulsations has been carried out. This asteroseismic work is specially important for the determination of the internal abundances of this kind of stars, a previous step to understand the physical mechanism responsible for the surface chemical peculiarities of the λ Bootis group. On the other hand, an analysis of the age determination of the planetary system HR 8799 has also been done. The results found in the literature are not conclusive, and the only valid argument to estimate the age of the star is that using its radial velocity and proper motion, but it is an estatistical argument needed of additional estimations.

The selection of models fulfilling the spectroscopic observations shows that there are no selected models with solar metallicity. This has an impact in the main assumption of the theory widely accepted to explain the λ Bootis nature, i.e. that these stars have solar metallicity, whereas the observed abundances are due to surface phenomena.

On the other hand, the main complementary argument to the kinematic age determination is the position of the star in the HR diagram. We have shown that, due to the λ Bootis nature of HR 8799, that hides the internal metallicity of the star, this HR diagram position provides a range of ages [10,2337] Myr, a much wider than that estimated by other authors of [30,160] Myr (Marois et al. 2008). Only a small amount (18.1%) of models in our grid have ages in the range claimed in the literature.

For inclination angles around $i = 36°$, the models fulfilling all the observational constraints have masses in two separate ranges of M=[1.32, 1.33], [1.44, 1.45] $M_\odot$, and the age of the system is constrained in two separate ranges: [1123, 1625] Myr and [26, 430] Myr respectively. A percentage of 16.7% of the models are in the range given in the literature. This determination has an impact in the determination of the mass of the objects observed orbiting around HR 8799.

A consequence of this study is the need for a precise determination of the inclination angle i, of the multicolour photometric amplitudes and phases of f_2, and some information of m values through time-series if high resolution spectroscopy. These determinations would help to carry out a definitive selection of the models. In any case, the range of ages assigned to this star in the literature is unlikely to be the correct one. Only a stellar luminosity larger than that reported would allow young models with solar metallicity to fulfill all the observational constraints.

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References

Barrado y Navascués, D.: 1998, Ap&SS 263, 235
Barrado y Navascués, D., Stauffer, J. R., Song, I., & Caillault, J.-P.: 1999, ApJ Letters 520, L123
Bayo A., Rodrigo C., Barrado y Navascués D., Solano E., Gutiérrez R., Morales-Calderón M., Allard F.: 2008, A&A 492, 277
Casas, R., Moya, A., Suárez, J. C., Martín-Ruíz, S., Amado, P. J., Rodríguez-López, C., & Garrido, R.: 2009, ApJ 697, 522
Casas, R., Suárez, J. C., Moya, A., & Garrido, R.: 2006, A&A 455, 1019
Chen C. H., Sheehan P., Watson D. M., Manoj P., Najita J. R.: 2009, ApJ 701, 1367
Gray, R. O. and Kaye, A. B.: 1999, AJ 118, 2993
Kaye, A.B. and Strassmeier, K.G.: 1998, MNRAS 294, 35
Kaye, A.B. et al.: 1999, PASP 111, 840
Lebreton, Y. et al.: 2008, Ap&SS 316, 1
van Leeuwen F.: 2007, A&A 474, 653
Marois, C. et al.: 2008, Sci 322, 1348
Morel P., Lebreton Y.: 2008, Ap&SS 316, 61
Moya, A., Garrido, R., Dupret, M. A.: 2004, A&A 414, 1081
Moya, A. et al.: 2005, A&A 432, 189
Moya, A. et al.: 2006, CoAst 147, 129
Moya, A., Garrido, R.: 2008, Ap&SS 316, 129
Moya, A., et al.: 2008: Ap&SS 316, 231
Moya, A., et al.: 2010a: accepted in MNRAS
Moya, A., et al.: 2010b: submitted to MNRAS Letters
Paunzen, E.: 2003, Recent. Res. Devel. Astronomy and Astrophysics 1, 1
Reidemeister M., Krivov A. V., Schmidt T. O. B., Fiedler S., Müller S., Löhne T., Neuhäuser R.: 2009, A&A 503, 247
Rodríguez, E. et al.: 2006a, A&A 450, 715
Rodríguez, E. et al.: 2006b, A&A 456, 261
Sadakane, K.: 2006, PASJ 58, 1023
Schuster, W.J. and Niessen, P.E.: 1986, IBVS 2943
Song I., Caillault J.-P., Barrado y Navascués D., Stauffer J. R.: 2001, ApJ 546, 352
Stello, D., et al.: 2009, ApJ 700, 1589
Su K. Y. L., et al.: 2009, ApJ 705, 314
Suárez, J. C. et al.: 2005, A&A 443, 271
Turcotte, S. and Charbonneau, P.: 1993, ApJ 413, 376
Zerbi, F.M., et al.: 1999, MNRAS 303, 275